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CAVITATION SIMILARITY CONSIDERATIONS BASED ON MEASURED PRESSURE AND TEMPERATURE DEPRESSIONS IN CAVITATED REGIONS OF FREON 114

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SUMMARY

Well-developed cavitation of Freon 114 (dichlorotetrafluoroethane) was induced on the walls of a venturi in a closed-return hydrodynamic tunnel. The venturi contained a convergent section to provide the transition from a 1.743-inch-diameter approach section to a 1.377-inch-diameter throat section. The approach velocity was varied from 19 to 44 feet per second and the bulk-liquid temperature from 5° to 80° F. Measured pressures and temperatures within the cavitated regions were in thermodynamic equilibrium at values less than free-stream (approach section) values of bulk-liquid temperature and its corresponding vapor pressure. At constant bulk-liquid temperature, maximum and average cavity pressure depressions below bulk vapor pressure increased almost directly with increased approach velocity. For a fixed velocity, the cavity pressure depression at 78° F was about 4.5 times that at 28° F. The maximum measured cavity-pressure depression at 78.4° F was 10.2 feet of liquid Freon 114. Similarity parameters for cavitation were developed by using minimum cavity pressure as a reference rather than bulk vapor pressure. Trends in the Freon 114 data and comparisons with previous measurements within cavities in water, nitrogen, and ethylene glycol in the same venturi are in reasonable agreement with those predicted from simple theoretical analyses.

INTRODUCTION

The noncavitating performance of pumps and other hydrodynamic devices such as venturis, orifices, valves, etc., can be predicted with reasonable accuracy from tests made in a reference fluid and simple, established laws of similarity. Conversely, cavitation performance cannot be accurately predicted when the fluid properties are different

from those of the reference fluid in which the flow device had been previously tested. Fluid properties have pronounced effects on cavitation performance. Observed effects of fluid properties on the inception of cavitation are reported in references 1 to 3 and for the more developed cavitation regimes in references 4 to 11. For example, incipient cavitation of nitrogen in a venturi (ref. 1) occurred at lower values of approach-section pressure head above vapor-pressure head than did similar operation with room-temperature water (ref. 3). Similar trends are reported regarding the inlet-above-vapor-pressure head that results in a specified drop in pump performance because of developed cavitation, as shown in references 6 to 8 and 10. A better understanding of fluid-property effects on cavitation is required to establish more refined similarity relations for use in design. Theories that propose to explain the fluid-property effects on cavitation performance are similar to those in reference 4. These studies have, in general, dealt with developed (rather than incipient) cavitation and, under certain simplifying assumptions, the thermodynamic effects that are believed to be involved. The main assumptions are that (1) there is a steady flow, (2) cavitation begins when local pressure is reduced to the vapor pressure of the bulk liquid, that is, no liquid tension, (3) the cavity is filled with vapor and the heat of vaporization is drawn from and later returned to the surrounding liquid, (4) change-in-phase processes and conditions within the cavity are in thermodynamic equilibrium, and (5) for pumps at least, there is a common critical volume ratio of vapor to liquid that applies to all fluids and beyond which performance rapidly decays, provided there is similarity of pump design and operating conditions.

Some of the current explanations of the cavitation process are described briefly in the following paragraphs.

Temperatures and pressures within cavitated regions are less than the inlet bulk-liquid temperature and corresponding vapor pressure by amounts dependent on fluid properties (confirmed experimentally for various liquids as shown in refs. 1, 9, 10, 12, and this report). Such local pressure depressions tend to inhibit cavity growth, and, thus, lower inlet pressure heads are necessary before a given volume of vapor is developed.

Methods for determining and specifying a critical volume of vapor or a vapor- to liquid-volume ratio have been proposed. For example, reference 13 relates critical vapor- to liquid-volume ratio to possible sonic-velocity limitations in a two-phase mixture.

Another aspect of the thermodynamic effects of developed cavitation is given by Hartmann and Ball (ref. 11): they suggest that the mechanism whereby a pump inducer, for example, can maintain its head rise at relatively lower inlet pressures is that the suction-surface pressures of the inducer blade can be lowered to the locally depressed vapor pressure rather than to the higher vapor pressure corresponding to the bulk-liquid temperature.

Present theories, at best, are useful to predict trends from one fluid to another, but

not to predict absolute values of cavitation limits for any one fluid or device. This is not surprising when the real complexities of the cavitation process, particularly in rotating machinery applications, are recognized. Experimental data are needed to confirm or revise present theoretical analyses so that reliable similarity parameters and design procedures that account for fluid-property effects on cavitation can be established.

Direct temperature and pressure measurements within cavities are very limited. Some results have been obtained with simple, nonrotating configurations that are easy to instrument and observe. In cavitation behind a disk (ref. 12) or on a venturi surface (ref. 1), measurements indicate negligible thermal effects in room-temperature water. Within nitrogen cavitation on the venturi (ref. 1), temperature and vapor-pressure depressions relative to bulk-liquid values as much as 3° F and 9 feet of liquid were obtained. In addition, pump results (ref. 6) indicate that the required net positive suction head (pump-inlet total-pressure head above vapor-pressure head at bulk-liquid temperature) with nitrogen is about 7 feet of liquid less than that with room-temperature water for the same measurable effects (performance decay) of cavitation.

This investigation provides additional insight into the effects of fluid properties on the cavitation process by measuring temperatures and pressures within cavitated regions of Freon 114 (dichlorotetrafluoroethane) flowing in the same transparent venturi used previously for water, nitrogen, and ethylene glycol (refs. 1 and 3). Freon 114 was selected because a study of the fluid properties of Freon 114 indicated that it would exhibit measurable thermodynamic effects of cavitation over an experimentally convenient range of temperature. These measurements are evaluated and compared with simple theoretical analyses. Conventional cavitation parameters are examined and new ones are proposed to account for varying fluid-property effects. The study was conducted at the NASA Lewis Research Center. Various amounts of well-developed cavitation were induced on the walls of a venturi section with 1.377-inch-diameter throat. The flow velocity in the venturi approach section (1.743-in. diam) was varied from 19 to 44 feet per second, and the liquid temperature was varied between 5° and 80° F. These ranges of velocity and temperature were determined by facility limitations.

APPARATUS

The facility used in the present study is the same as that described in detail in references 1 and 2. Briefly, it consists of a small closed-return hydrodynamic tunnel (capacity, approximately 10 U.S. gal) designed to circulate various liquids by a 700-gallon-per-minute centrifugal pump. Static-pressure level in the tunnel was varied by gas pressurization of the ullage space above a butyl rubber diaphragm in the tunnel expansion chamber. A liquid bath (capacity, approximately 80 U.S. gal) surrounds the tunnel to serve as

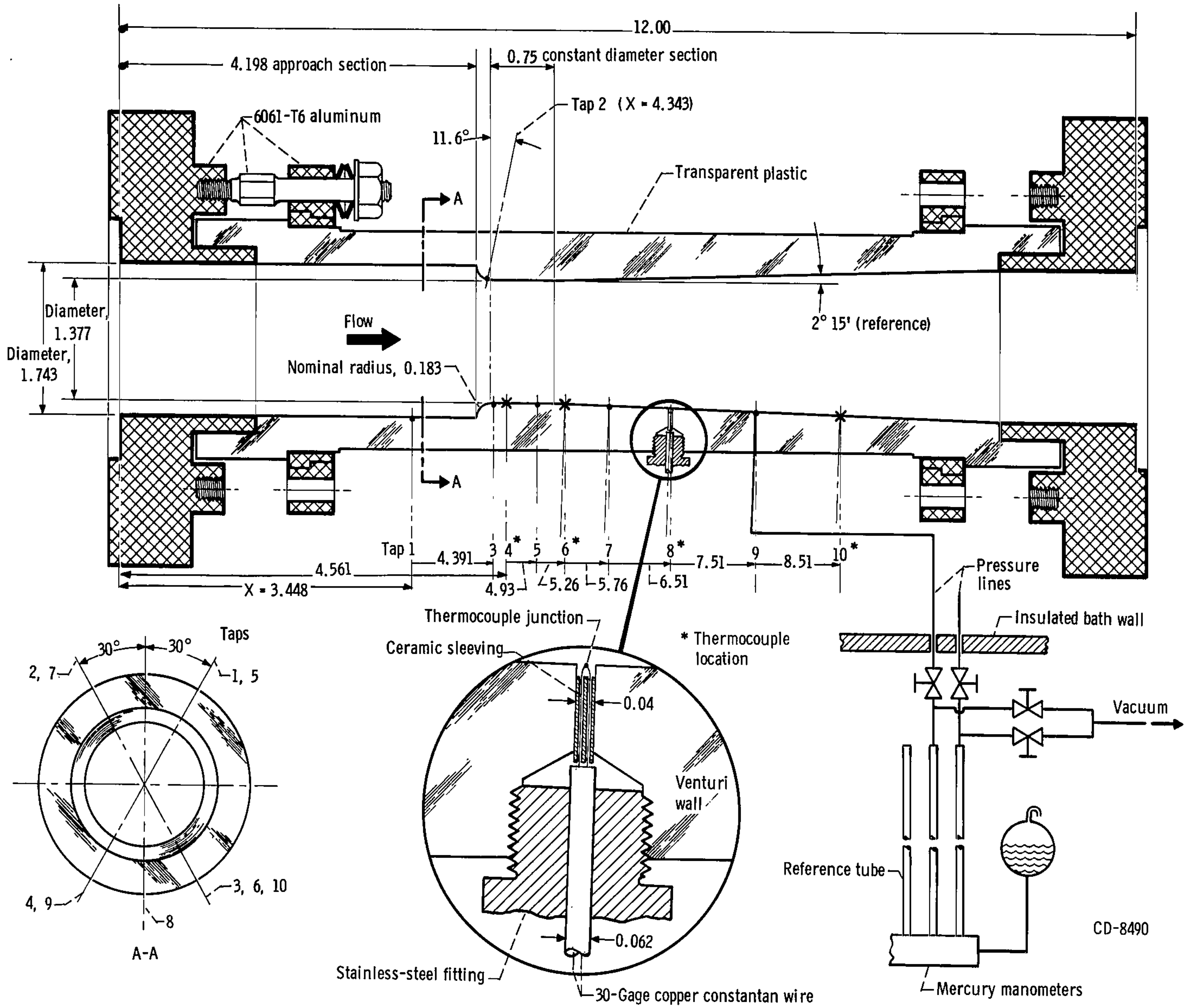


Figure 1. - Schematic drawing of venturi test section. (All dimensions are in inches.)

a heat sink and to control tunnel liquid temperature. For temperature control, a slowly circulated bath mixture of ethylene glycol and water was used. This mixture exchanged heat with a sump-mounted single-tube coil carrying either low-pressure steam or cold nitrogen gas.

The transparent-plastic venturi test section shown in figure 1 is the same one used in previous cavitation studies with water, nitrogen, and ethylene glycol (refs. 1 to 3 and 14). The venturi used a slightly modified quarter-round (nominal rad., 0.183 in.) to provide the transition from a 1.743-inch-diameter approach section to a 1.377-inch-diameter throat section. The 0.75-inch-long constant-diameter throat is followed by a conical diffuser.

For velocity determination, static pressures were measured across the tunnel contraction nozzle (not shown herein, see ref. 1) just upstream of the test section, as shown in figure 1. Contraction nozzle pressures and those from tap 1 (fig. 1) were measured by calibrated bleed-type precision gages (accuracy, ±0.15 psi). All free-stream values refer to the axial location of tap 1 (fig. 1). There are nine instrumentation tap locations on the venturi, five (2, 3, 5, 7, and 9) were pressure taps connected to a 4-foot-high multiple-tube mercury manometer, and four (4, 6, 8, and 10) were fitted with nearly flush copper-constantan thermocouples, as indicated in figure 1. To minimize hydrostatic head corrections, all pressure lines were arranged in a horizontal plane on the venturi centerline and within the bath liquid; from here the lines are connected to the manometers or gages. As shown in figure 1, the thermocouple junctions (open-ball type) were mounted to coincide with the venturi inner wall contour, but they did not contact the wall. The calibrated thermocouple circuit was designed to measure the temperature difference between a venturi inner-wall location and an upstream-liquid reference. The reference tunnel liquid temperature was measured by a calibrated copper-constantan thermocouple mounted on the flow centerline 14.5 inches upstream from tap 1 (fig. 1). Calibration studies indicated that the temperature differences were measured with an accuracy of ±0.05° F and tunnel liquid temperatures with an accuracy of ±0.15° F.

Cavitation was photographed by a 4- by 5-inch still camera in conjunction with a 0.5-microsecond high-intensity flash unit.

PROCEDURE

Test Liquid

A commercial grade of Freon 114 (dichlorotetrafluoroethane), a clear, colorless liquid with a normal boiling point of 38.8° F, was used as the test liquid. Some properties of liquid Freon 114 are presented in references 2, 15, and 16.

The hydrodynamic tunnel, initially evacuated and cooled to below 38° F, was charged

twice with Freon 114 (the same two charges that resulted in the incipient cavitation data of ref. 2). One charge was made directly from the cylinder as it was received from the manufacturer, who specifies a noncondensable gas content (assumed to be air) less than 20 parts per million (ppm, mg air/kg liquid). The other charge was reprocessed at the test site; its air content is not known. For reference, at a total pressure (air plus vapor) of 1 atmosphere, air-saturated Freon 114 contains about 140 parts per million at 32° F and about 1000 parts per million at 0° F. Both charges gave the same results.

Facility Operation and Measurement Techniques

With a fixed pump speed, the bath liquid temperature was adjusted until tunnel liquid temperature was at the desired level. Next, the free-stream static pressure was decreased to a level below that for noncavitating flow and, thus, a nominally fixed length of cavity was generated. Temperatures and pressures within the cavitated region, which quickly stabilized, were then measured, and the cavity was photographed. During this time, the tunnel liquid temperature was constant within $\pm 0.1^{\circ}$ F. At higher pump speeds, corresponding higher free-stream pressures were required for the same length of cavity. Four different cavity lengths were generated at each of several pump speeds and tunnel liquid temperatures. Nominal cavity lengths of $\frac{1}{2}$, $1\frac{1}{4}$, $2\frac{3}{4}$, and 4 inches were selected mainly on the basis of the pressure-tap and thermocouple locations of figure 1. Each successive increase in cavity length allowed additional pressure-tap and thermocouple locations to be included within the cavity. For a fixed pump speed, free-stream velocity decreased slightly with increased cavity length because of increased total head losses.

To minimize air contamination of the tunnel liquid, all pressure lines and manometer tubes were evacuated before the tunnel was filled. The valves between the venturi and the manometers (see fig. 1) were closed after this evacuation. For the pressure measurements within a cavitated region, a manometer tube was opened only after cavitation was developed over the coresponding pressure-tap location. Downstream taps were similarly activated as the cavity was lengthened. In this way, the pressure lines and manometer tubes contained either all Freon vapor, or Freon vapor plus a possible liquid-Freon head not exceeding $\pm 3/4$ inch within the bath liquid. This hydrostatic head was possible for cases where the bath temperature was less than the cavity temperature, but because of its uncertainty, no correction was made. The reference liquid temperature of the tunnel is slightly warmer (0.3° F, maximum) than the free-stream liquid temperature. This axial temperature drop (in 14.5 in.) is a result of the transfer of part of the heat energy added by the pump to the bath liquid. The free-stream liquid temperatures presented herein account for this difference.

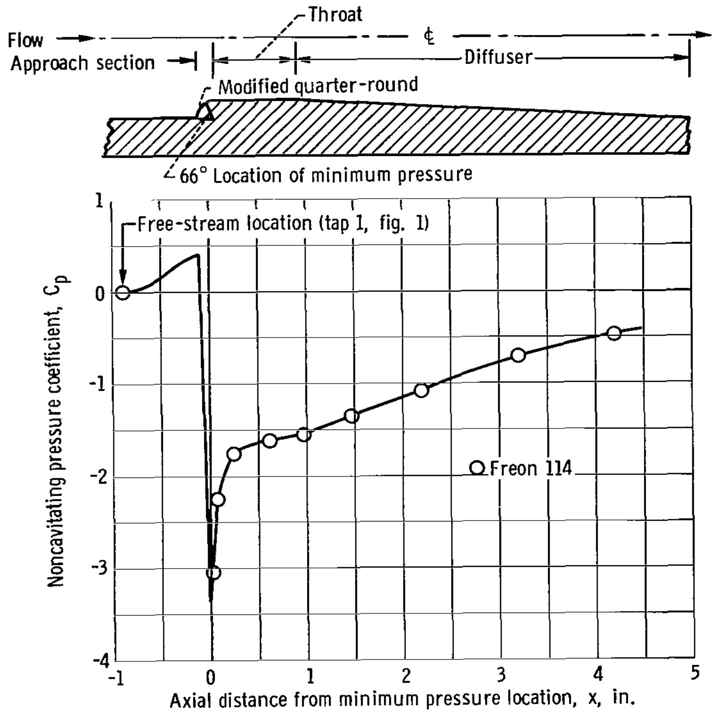


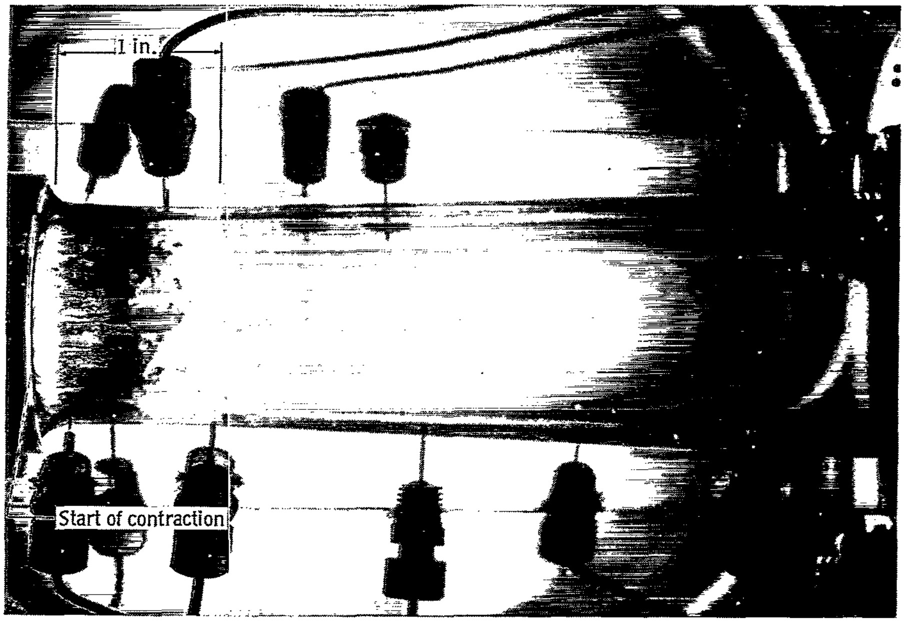
Figure 2. - Noncavitating pressure distribution for venturi operating above critical Reynolds number (curve and data from refs. 1 and 2).

RESULTS AND DISCUSSION

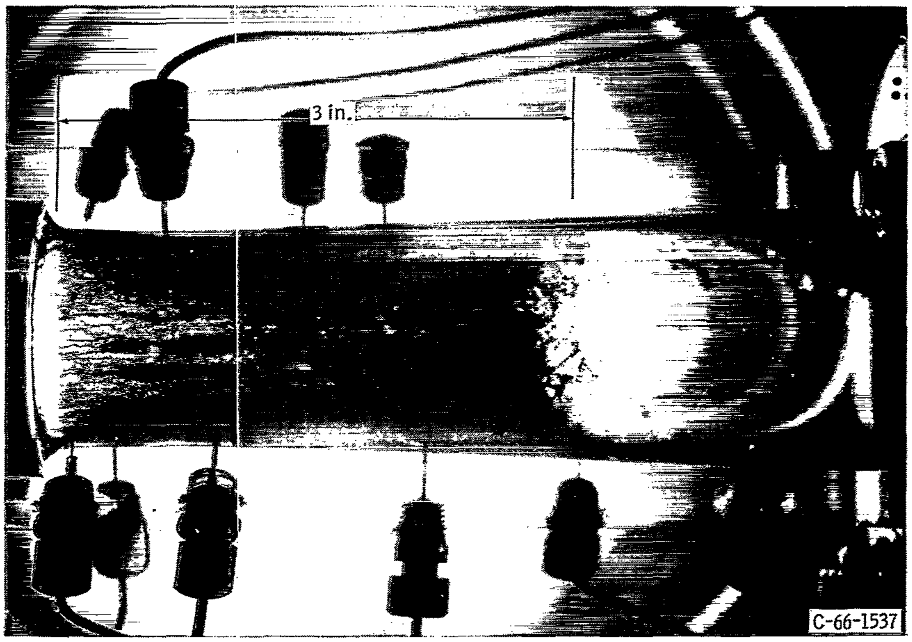
Characteristics that were common to all the experimental Freon 114 results are presented first, followed by specific trends in cavity temperature and pressure depressions. Similar results for several liquids are then examined, and, finally, a comparison of experimental with a simple theoretical approach is presented.

Characteristics Common to All Experimental Results

Noncavitating pressure distribution. - The pressure coefficient, C_p as a function of axial distance x from the minimum pressure location is presented in figure 2. The minimum pressure location is at a value of X of 4.307 inches (see fig. 1), or 66^{o} of arc from the leading edge of the quarter-round section. (All symbols are defined in the appendix.) Various fluids and two model sizes have been used to establish the venturi wall pressure distribution. These results have been reported (refs. 1 and 2), and a typical pressure distribution is presented in figure 2 for convenient reference. The curve of



(a) Nominal cavity length, 1/2 inch; free-stream velocity, 33.1 feet per second; free-stream static pressure, 73.0 feet; developed cavitation parameter, K_v, 2.27; developed cavitation parameter $K_{c,min}$, 2.49.



(b) Nominal cavity length, $2\frac{3}{4}$ inch; free-stream velocity, 31.8 feet per second; free-stream static pressure, 66.4 feet; developed cavitation parameter, K_v, 2.04; developed cavitation parameter $K_{c,min}$, 2.37.

Figure 3. - Typical appearance of cavitated Freon 114 for free-stream liquid temperature of 59.1° F. (Flow direction is from left to right.)

figure 2 is actually well defined from aerodynamic measurements made on a large scale model, although these data are not shown.

Appearance of developed cavitation. - Typical photographs of 1/2- and $2\frac{3}{4}$-inch-long cavities are shown in figure 3. Free-stream conditions were nominally the same for both lengths, except for h_0, which was less for the longer cavity. For the range of conditions studied herein, a change in free-stream liquid temperature or velocity does not change the appearance of fixed-length Freon 114 cavitation. The cavitation is composed of many individual vapor streamers around the circumference of the venturi that merge within a few tenths of an inch downstream from the leading edge of the cavity to form a thin annulus of a frothy and turbulent vapor-droplet mixture adjacent to the wall. The leading edges of these streamers remain fixed near the noncavitating minimum pressure location (see fig. 2). Photographs indicate that the cavity leading edge is less than 0.1 inch downstream from this minimum pressure location. The trailing edges of all cavitated regions are rather uniform and well defined. Most of the vapor generated by cavitation appears to condense within the nominal cavity lengths specified and there is no visible change in this for Freon 114 over the 5° to 80° F temperature range studied. Cavitation was observed to be of the fixed (or steady) type rather than the traveling (or transient) type and was similar to that described for water in reference 14. Within the 1.377-inch-diameter throat of the venturi, the nominal thickness of the cavitated region is estimated to be of the order of 0.020 inch, although no direct measurements were made. Thus, a large part of the venturi flow remains single phase (liquid) under all conditions of cavitation studied herein.

Effects of cavitation on local pressures and temperatures. - Within the cavitated region, local pressures and temperatures are less than free-stream values, and typical results for the $2\frac{3}{4}$-inch-long cavity shown in figure 3 are given in figure 4. Cavity pressure depressions are presented as a function of axial distance from the noncavitating minimum pressure location. These measured pressure depressions are relative to free-stream vapor pressure (vapor pressure corresponding to free-stream liquid temperature). In addition, the measured temperature depressions (relative to free-stream liquid temperature) were converted to the corresponding vapor-pressure depressions and were plotted. Conversion from temperature to vapor pressure

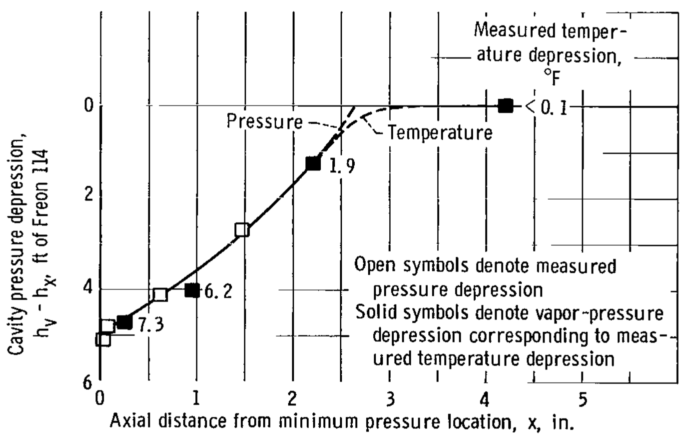


Figure 4. - Typical pressure and temperature depressions within cavitated Freon 114 region. Nominal cavity length $2\frac{3}{4}$ inches; free-stream velocity, 31.8 feet per second; free-stream static pressure, 66.4 feet; liquid temperature, 59.1° F; developed cavitation parameter K_v, 2.04; developed cavitation parameter $K_{c,min}$, 2.37; (see fig. 3(b)).

was made by use of thermodynamic tables (ref. 15). With the instrumentation used, the measured pressures and temperatures reflect time-averaged values. There is reasonably good agreement between the measured pressure depressions and the depressions based on locally measured temperatures. The measured pressure depressions of figure 4, and subsequent data, tend to be a little less (of the order of 1/2 ft of Freon 114 or about 0.3 psi) than that indicated by vapor pressure at measured temperatures. At least part of this pressure increment is attributed to the partial pressure of liberated gases in the cavitated region. The assumption of a gas (air) content of 20 parts per million and infinite diffusion time can yield the partial pressures required for perfect thermodynamic agreement, that is, equilibrium. For engineering purposes, cavity pressures and temperatures are considered to be in thermodynamic equilibrium herein.

The maximum measured pressure and temperature depressions occur near the leading edge of the cavitation and for the conditions of figure 4 are 5.1 feet of Freon 114 and 7.3° F, respectively. (The maximum measured pressure depressions at $x = 0.038$ in. are believed representative of those at $x = 0$ in.) The location at which the pressure and temperature depressions approach zero, at a value of x of $2\frac{3}{4}$ inch, approximates the end of the cavitated region (fig. 3(b)). Downstream from the cavity collapse region, the liquid along the wall returns to the free-stream liquid temperature as indicated by the dashed line in figure 4. Also, the absolute value of wall pressure rapidly increases in this region and approaches, but does not equal (because of energy losses due to mixing), the noncavitating value of the pressure (see ref. 1).

Similarity parameters for developed cavitation. - The conventional cavitation parameters for dynamic similarity of flow are of the form

$$K \equiv \frac{h_0 - h_v}{\dfrac{V_0^2}{2g}} \tag{1}$$

where the free-stream static pressure and velocity are those that produce the cavity size of interest, and h_v is the vapor pressure that corresponds to free-stream liquid temperature. For a particular V_0, there is a value of h_0 that produces incipient cavitation. Lower values of h_0 can produce developed cavitation of any desired length (ref. 17). The different subscripts used with K denote particular cavitation parameters (e.g., K_v for developed cavitation and K_{iv} for incipient cavitation, both based on h_v). The developed cavitation parameter K_v stems from assuming that Bernoulli's equation for steady ideal flow applies between the free-stream location and the cavity surface, and that the cavity surface is at a constant pressure equal to the free-stream vapor pressure. A more general statement for cavitation parameters would replace h_v in equation (1)

with h_c, the actual pressure in the cavity, which may differ from free-stream vapor pressure. The pressure within the cavitated region of Freon 114 is less than the free-stream vapor pressure and is not constant with axial length (fig. 4), so that the selection of a reference cavity pressure is required. The minimum measured cavity pressure is used in this report to define a developed cavitation parameter:

$$K_{c,min} \equiv \frac{h_0 - h_{c,min}}{\frac{V_0^2}{2g}} = K_v + \frac{h_v - h_{c,min}}{\frac{V_0^2}{2g}} \qquad (2)$$

For a fixed cavity length, the value of $K_{c,min}$ will be shown to be nearly constant over a range of velocities and temperatures, whereas K_v varies considerably and is thus less useful as a similarity parameter. For the conditions of figure 4, the value of K_v was 2.04 and $K_{c,min}$ was 2.37. Although $h_{c,min}$ was measured for this study, it is not generally available or, at present, predictable for an arbitrary fluid, model, or velocity. A method of estimating $h_{c,min}$ for a given model with various liquids is discussed in a later section. This method depends on knowing a value of $h_{c,min}$ for the given model, tested in a liquid that demonstrates a substantial fluid-property effect.

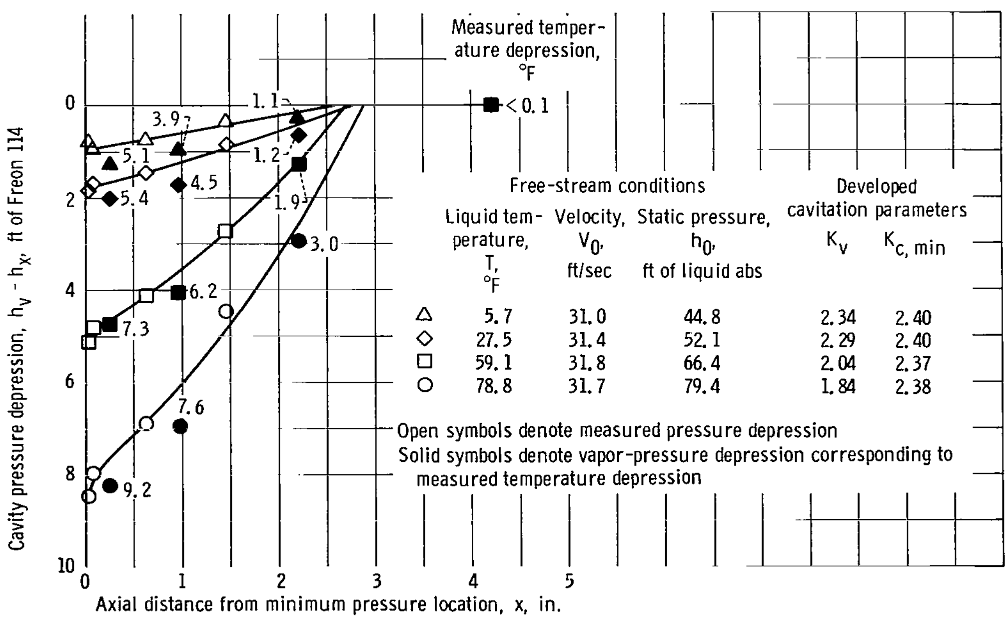


Figure 5. - Effect of free-stream liquid temperature on pressure and temperature depressions within cavitated Freon 114 region for nominal cavity length of $2\frac{3}{4}$ inches.

Specific Trends in Cavity Temperature and Pressure Depressions

Effect of free-stream temperature. - Increasing the liquid temperature from 5.7° to to 78.8° F increases the depression of cavity pressures and temperatures over the full axial length of the cavity, as shown in figure 5. Free-stream velocity and cavity length were nominally constant at 31.4 feet per second and $2\frac{3}{4}$ inches, respectively. The maximum measured pressure depression for 78.8° F liquid Freon 114 is 8.5 feet, which is approximately 1.7 times that for 59.1° F, 4.6 times that for 27.5° F, and 9.3 times that for

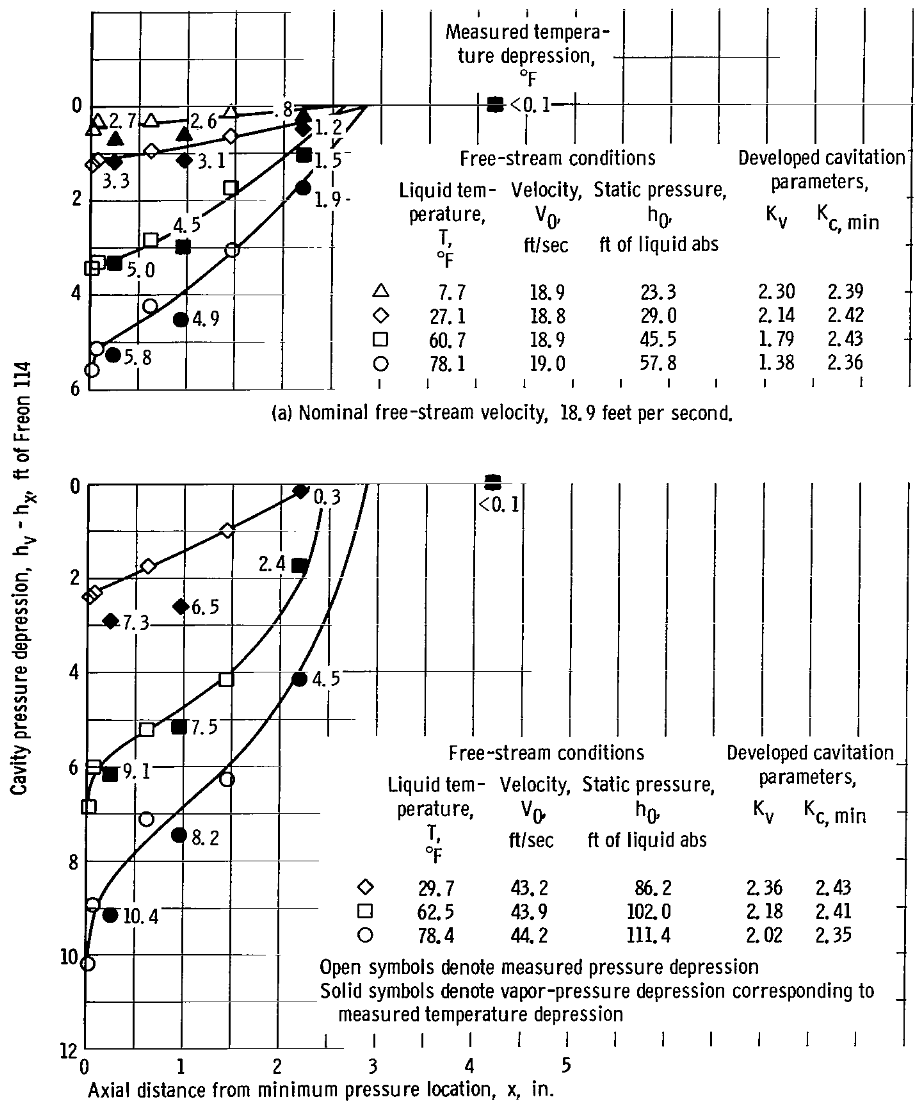


Figure 6. - Effect of free-stream velocity on pressure and temperature depressions within cavitated Freon 114 region at several liquid temperatures for nominal cavity length of $2\frac{3}{4}$ inches.

5.7° F liquid. Integrated average pressure depressions (over the axial length of cavity) show about the same ratios.

The cavitation parameter K_v decreases continuously from 2.34 to 1.84 as temperature is increased from 5.7° to 78.8° F, although the length of the cavity was held nominally the same ($2\frac{3}{4}$ in.). In contrast, the parameter $K_{c,min}$ is essentially constant, varying in a random manner between 2.37 and 2.40.

Effect of free-stream velocity. - An increase in velocity from about 18.9 feet per second (fig. 6(a)) to 43.8 feet per second (fig. 6(b)) results in a nearly twofold increase in maximum cavity pressure depressions. This same ratio holds for each of the three temperature levels, nominally 78°, 61°, and 28° F, for which comparable data are presented. The cavity length was held constant at $2\frac{3}{4}$ inches. The maximum measured cavity pressure and temperature depressions of figure 6 are 10.2 feet of Freon 114 and 10.4° F, which occurred with a free-stream velocity of 44.2 feet per second and a free-stream liquid temperature of 78.4° F.

The cavitation parameter $K_{c,min}$ for all the data in figure 6 remains nearly constant, varying in a random manner between 2.35 and 2.43. These data cover a velocity range from 18.8 to 44.2 feet per second and a temperature range from 7.7° to 78.4° F. In contrast, K_v increased with increasing velocity and decreased with increasing temperature, with a maximum variation from 1.38 to 2.36 as indicated in figure 6.

Effect of cavity length. - With the cavity length increased from 1/2 to 4 inches, the pressure and temperature depressions increased throughout the cavity, as shown in figure 7. The free-stream velocity was nearly constant at about 32 feet per second, and the temperature was 59.1° F. Photographs corresponding to the 1/2- and $2\frac{3}{4}$-inch data are shown in figure 3. The axial location where the local cavity pressure h_x appears to equal vapor pressure h_v (fig. 7) coincides closely with the end of visible cavitation, as shown by the photographs in figure 3. The value of K_v decreased continuously

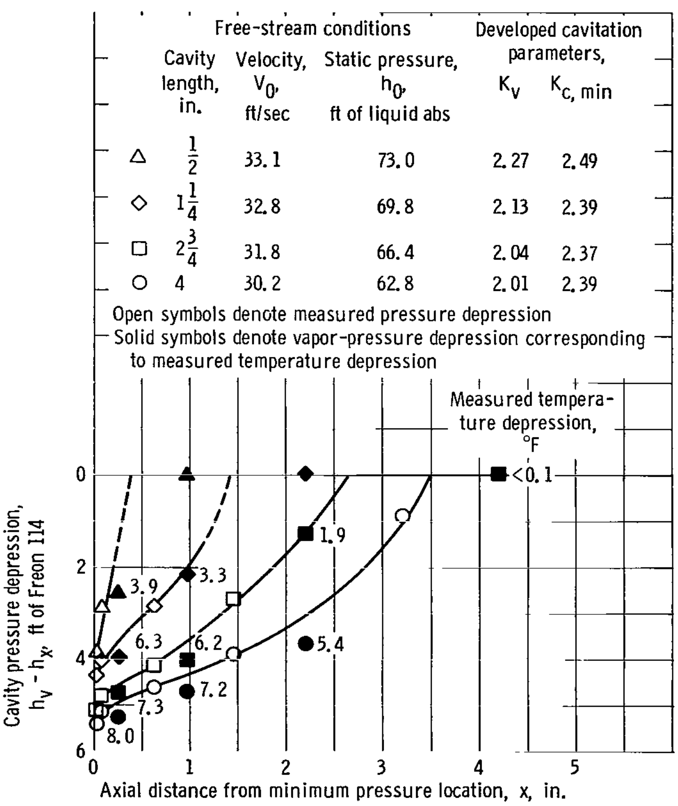


Figure 7. - Effect of cavity length on pressure and temperature depressions within cavitated Freon 114 regions for free-stream liquid temperature of 59.1° F.

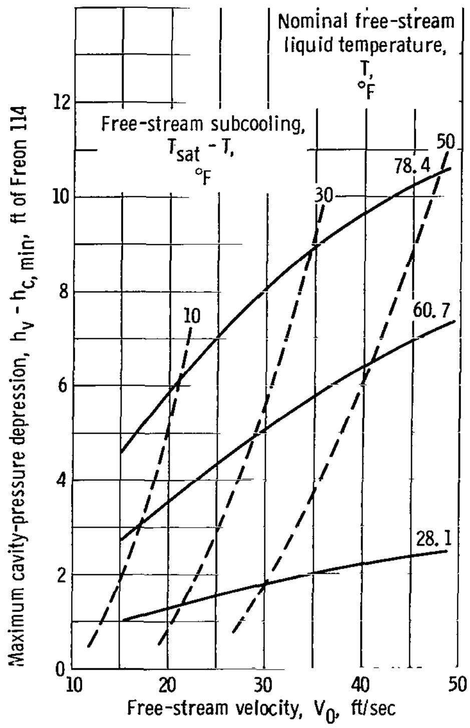


Figure 8. - Effects of free-stream velocity and free-stream liquid temperature on maximum pressure depression within cavitated Freon 114 region for nominal cavity length of $2\frac{3}{4}$ inches.

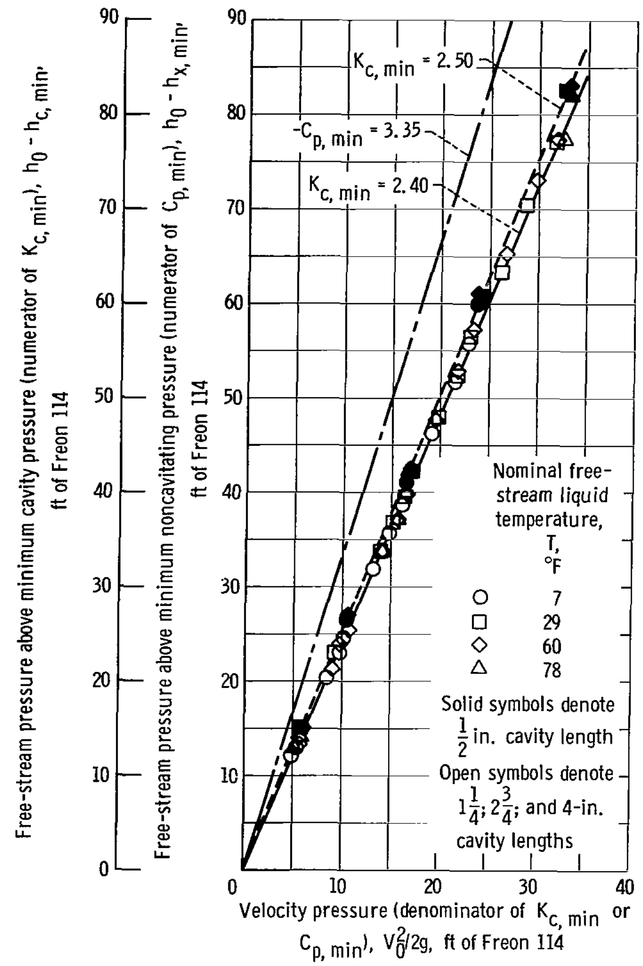


Figure 9. - Effects of free-stream velocity and free-stream liquid temperature on minimum pressure in cavitated Freon 114 region, and, for reference, minimum noncavitating pressure.

with increased cavity length (fig. 7). The value of $K_{c,min}$ decreased as the length increased from 1/2 to $1\frac{1}{4}$ inches but tended toward a constant value for cavity lengths > $1\frac{1}{4}$ inches.

Summary of Cavity Depression Effects for Freon 114

The maximum pressure depressions within $2\frac{3}{4}$-inch-long cavities over a range of velocities and temperatures are summarized in figure 8. The free-stream subcooling parameter T_{sat} - T superimposed on the figure is for convenient reference. The maximum depressions increase almost directly with increased velocity at constant temperature, and increase continuously with increased temperature at constant velocity. Also, at constant velocity, the maximum pressure depressions increase exponentially with de-

creased subcooling of the free stream. The free-stream subcooling parameter may prove more meaningful than a temperature level when different liquids are compared. Integrated average cavity pressure depressions show trends similar to the maximum depressions shown herein.

The degree to which the parameter $K_{c,min}$ is constant for the range of conditions studied is shown graphically in figure 9, where the numerator of $K_{c,min}$ is plotted as a function of its denominator. As shown by the slopes, $K_{c,min}$ can be represented by two values: 2.50 (±0.03) for $\frac{1}{2}$-inch cavity length, and 2.40 (±0.04) for $1\frac{1}{4}$-, $2\frac{3}{4}$-, and 4-inch lengths. These values are independent of temperature and include data at intermediate velocities not previously presented. For reference, figure 9 also shows the numerator of $-C_{p,min}$, the noncavitating minimum pressure coefficient. As shown by the slope, $C_{p,min}$ is -3.35 (see also fig. 2). Thus, if the same V_0 and h_0 are assumed, the minimum noncavitating pressure is always lower than that within a cavitated region at approximately the same axial location. Actually, at the same V_0, the value of h_0 with cavitation present is always somewhat less than that for noncavitating flow, so that the assumptions in the previous statement are conservative.

Comparison of Cavity Pressure and Temperature Depressions for Various Liquids

Nitrogen. - For comparison, the nitrogen cavity pressure and temperatures reported in reference 1 are given in figure 10. (Nitrogen property values are taken from refs. 18 and 19.) Photographs of nitrogen cavitation corresponding to the lowest velocity data of figure 10 are shown in figures 11(a) and (c). Cavity pressure and temperature depressions with nitrogen show trends that are similar to those for Freon 114; namely, that approximate thermodynamic equilibrium exists within the cavity and that the maximum pressure depressions occur near the leading edge of the cavity. Nitrogen cavities less than 1 inch long were not studied. The absolute values of cavity pressure depression, in feet of liquid, are the same order of magnitude for nitrogen as for Freon 114 with the best agreement obtained with the warmest (~80° F) Freon. With nitrogen, the 2.6° F increase in free-stream liquid temperature with increased velocity from 19.2 to 42.0 feet per second tends to mask the independent effects of velocity and temperature, but together their increase results in increased depressions of cavity temperature and pressure.

A photographic comparison of nitrogen at -320° F and Freon 114 at 78.1° F is shown in figure 11 for a nominally constant free-stream velocity of 19.4 feet per second. These photographs correspond to the nitrogen data of figure 10 and Freon 114 data of figure 6(a).

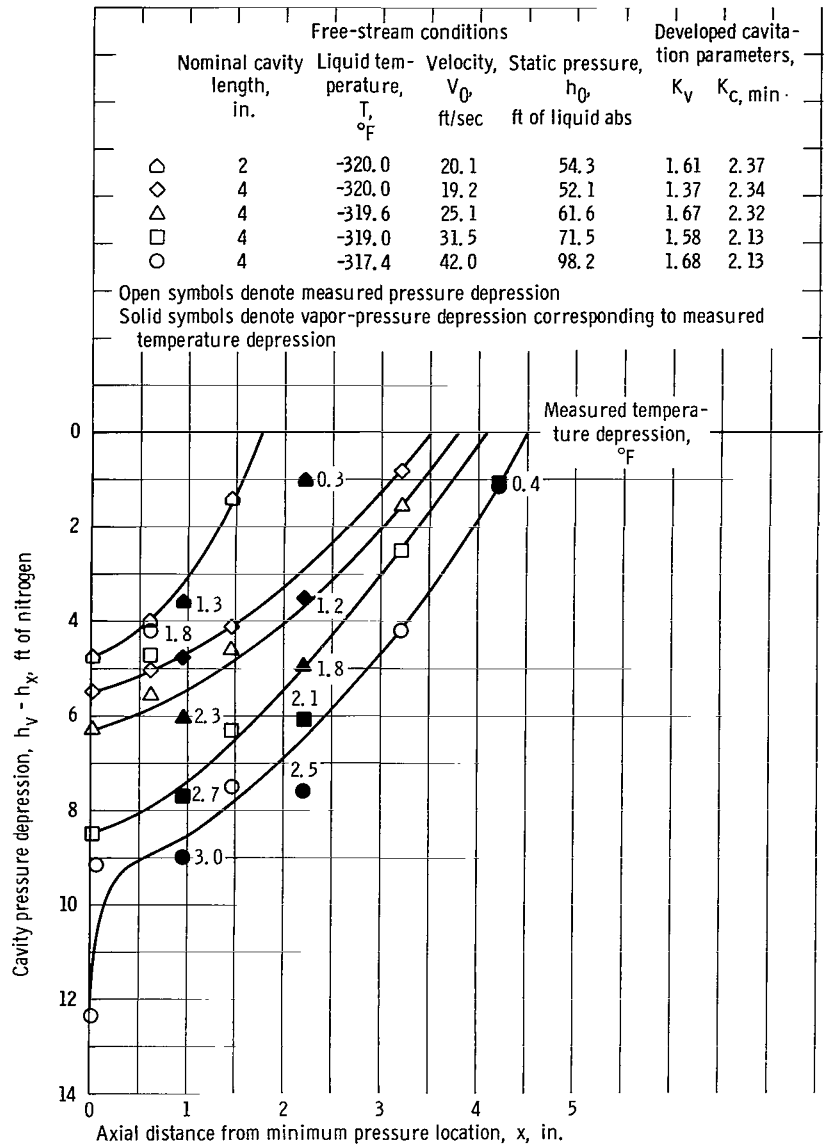
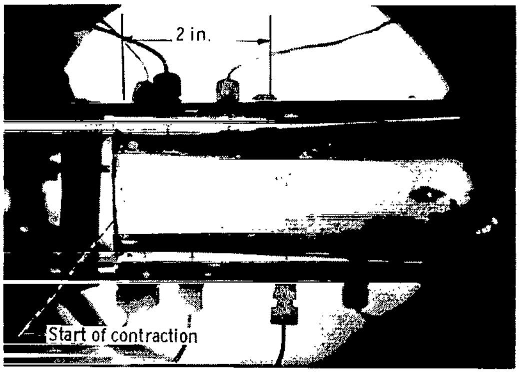
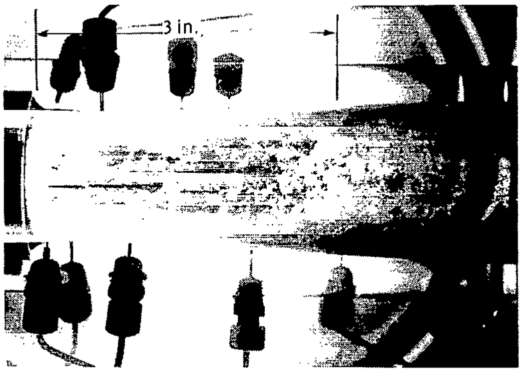


Figure 10. - Pressure and temperature depressions within cavitated nitrogen region (data from ref. 1).

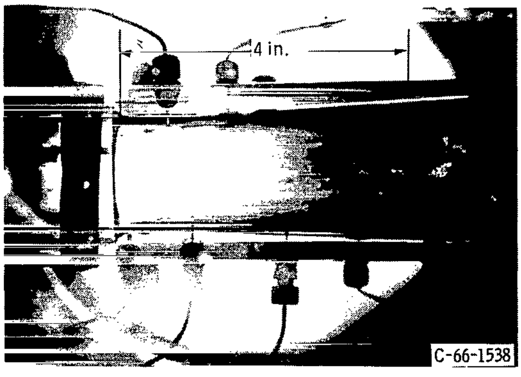
Compared with Freon 114, the main visible difference is that the nitrogen cavitation has a less stable leading edge and is less uniformly developed circumferentially. Generally, for the range of conditions studied, Freon 114 cavitation (0° F $< T <$ 80° F) more nearly resembles that for water (70° F $< T <$ 125° F, see ref. 14) than that for nitrogen (-320° F $< T <$ -316° F). Like water, Freon 114 cavitation appears more violent and is noisier than nitrogen cavitation for similar velocities and cavity lengths. For reference, the approximate free-stream subcooling $T_{sat} - T$ was $\leq 10^{\circ}$ F for nitrogen, 10° to 70° F for Freon 114, and 85° to 140° F for water.



(a) Nitrogen; nominal cavity length, 2 inches (fig. 10); free-stream velocity 20.1 feet per second; free-stream static pressure, 54.3 feet of nitrogen; temperature, -320° F; developed cavitation parameter K_v, 1.61; developed cavitation parameter, $K_{c,min}$, 2.37.



(b) Freon 114; nominal cavity length, $2\frac{3}{4}$ inches (fig. 6(a)); free-stream velocity, 19.0 feet per second; free-stream static pressure, 57.8 feet of Freon 114; temperature 78.1°F; developed cavitation parameter K_v, 1.38; developed cavitation parameter $K_{c,min}$, 2.36.



(c) Nitrogen; nominal cavity length, 4 inches (fig. 10); free-stream velocity, 19.2 feet per second; free-stream static pressure, 52.1 feet of nitrogen; temperature, -320° F; developed cavitation parameter K_v, 1.37; developed cavitation parameter $K_{c,min}$, 2.34

Figure 11. - Comparative appearance of nitrogen and Freon 114 cavitation at same free-stream velocity. Nitrogen photographs are taken from reference 1. (Flow direction is from left to right.)

With nitrogen, as with Freon 114, $K_{c,min}$ is closer to a constant value than is K_v (fig. 10). The $K_{c,min}$ for 2- and 4-inch nitrogen cavities was 2.37 and 2.34, respectively, for the same free-stream velocity (~19.6 ft/sec) and liquid temperature (-320° F). With V_0 increased to 25.1 feet per second, $K_{c,min}$ only changed to 2.32. However, at V_0 equal to 31.5 feet per second, the value of $K_{c,min}$ decreased to 2.13 and remained there for a V_0 equal to 42.0 feet per second. The physical geometry of the nitrogen cavitation was observed to change as V_0 was increased. In particular, above a V_0 of about 30 feet per second, the leading edge of some of the cavity streamers became markedly erratic and was at times nearly 1 inch downstream from x of zero. Also, less of the circumference was covered by streamers. The cavity growth time apparently becomes too marginal with nitrogen at the higher velocities to assure a well-defined leading edge. Tendencies toward this erratic cavity leading edge are visible in figures 11(a) and (c). However, for nitrogen cavitation with leading-edge geometry and overall length similar to that of the Freon 114 cavitation, the nitrogen $K_{c,min}$ was 2.35 (±0.03) and the Freon 114 $K_{c,min}$ was 2.40 (±0.04). With nitrogen, the values of K_v ranged from 1.37 to 1.67, while with Freon 114, the values of K_v varied from 1.38 to 2.30.

Water and ethylene glycol. - These two liquids had been previously tested in the same venturi for cavity temperature and pressure effects. The water and the glycol data were limited to a maximum free-stream liquid temperature of about 125° F and maximum velocity of about 45 feet per second. For these

TABLE I. - DEVELOPED CAVITATION PARAMETER

FOR SEVERAL LIQUIDS BASED ON MINIMUM

CAVITY PRESSURE

Liquid	Free-stream conditions		Cavity length, in.	
	Liquid temperature, T, ^{o}F	Velocity, V_0, ft/sec	1/2 (a)	1 to 4 (a)
Freon 114	0 to 80	19 to 45	2.50	2.40
Nitrogen	-320	19 to 25	Not available	2.35
Water	70 to 125	19	2.28	2.20
		45	2.51	2.37
		>45	[b]2.53	[b]2.39
Ethylene glycol	70 to 100	19	1.73	1.73
		45	2.25	2.25
		~70	[b]2.35	[b]2.35
	125	19	1.81	1.73
		45	2.33	2.25
		~70	[b]2.43	[b]2.35

[a]All values are within ±0.03.
[b]Estimated.

conditions and 4-inch-long cavities, the maximum measured temperature depressions were about 0.3° F, nearly the same for both liquids. The corresponding vapor pressure drop within the cavities is negligible.

With these negligible thermal effects of cavitation, there is no difference between h_v and $h_{c,min}$ and thus, from equation (2), $K_{c,min}$ equals K_v for water and for ethylene glycol at the temperatures studied. The parameter $K_{c,min}$ applies to all liquids whether or not there are thermal effects of cavitation. The values of $K_{c,min}$ for water and for ethylene glycol are given in table I together with a summary of Freon 114 and nitrogen values.

Summary of developed cavitation parameter based on minimum cavity pressure for several liquids. - The values of $K_{c,min}$ in table I are for geometrically similar cavities. The values of $K_{c,min}$ for water for cavity lengths of about 1/2 inch were greater than those for cavity lengths of 1 to 4 inches; the longer lengths could not be separately identified by the $K_{c,min}$ value. Similar results were obtained with Freon 114. In contrast to Freon 114, values of $K_{c,min}$ for water increase about 10 percent as V_0 in-

creases from 19 to 45 feet per second but tend toward a constant value at high velocity. The lower values of V_0 for water data appear to reflect something like a subcritical Reynolds number effect on the flow field. The actual relation or reason for this trend is not presently known.

It is difficult to evaluate a comparison of the values of $K_{c,min}$ for glycol with the other liquids because $C_{p,min}$ changes with V_0 and, hence, the cavitation is occurring in a dissimilar flow field. The Reynolds number range of operation for glycol is an order of magnitude less than the lowest value of the other liquids studied and is definitely subcritical, as shown in reference 3.

For cavities about 1 to 4 inches long, a value of $K_{c,min}$ near 2.37 applies for Freon 114 and water, both over a range of temperatures, and for nitrogen near its normal boiling point. A value of $K_{c,min}$ near 2.51 applies for 1/2-inch cavities of Freon 114 and water, if the water is at high V_0. Data for 1/2-inch cavities of nitrogen are not available.

Comparison of Experimental Results with Simple Theoretical Analyses

Some theoretical analyses are presented first. Then comparisons between experiment and theory are made regarding the effects of temperature, velocity, and liquid on the cavity pressure depressions for geometrically similar cavities. Finally, a method for estimating h_0 for similar cavity lengths in other liquids with thermal effects is discussed, as are the assumptions involved in the simple theories.

Theoretical analyses. - The temperature depressions measured within a cavitated region are attributed to liquid cooling along the vapor-liquid interface because of the heat of vaporization drawn from a thin layer of adjacent liquid. If the conditions within the cavity are in thermodynamic equilibrium (and there are no partial pressures of permanent gases), the cavity pressure should drop to the vapor pressure corresponding to the reduced local temperature. In general, these temperature and pressure depressions are a function of fluid properties as well as the complicated geometry, velocities, and heat- and mass-transfer mechanisms involved.

By simplifying assumptions to the energy, momentum, and continuity equations (and neglecting of some terms from an order of magnitude comparison) it follows from equation (15) of reference 8 that starting with a 1-pound mass of liquid,

$$wL = (1 - w)\Delta H_f \tag{3}$$

The numerous assumptions and development of equations leading to equation (3) are detailed in reference 8. For the present usage, the main assumptions of the simplified theory are believed to be (1) steady flow, (2) negligible net work and heat transfer during

the vaporization (flashing) process, (3) no surface tension considerations, (4) negligible body forces, (5) no liquid tension, and (6) fluid in thermodynamically stable equilibrium throughout the process. Reference 4 also develops equation (3) in a different, less detailed approach. Reference 20 shows the equivalence of the various developments to a simple static model. A description of this static model follows: Consider a 1-pound mass of liquid that fills an insulated container which has a tightly fitting piston. With an increase in total volume (attained by lifting the piston within the container), an increment of liquid is vaporized. The energy change is entirely a change in enthalpy, which goes into vaporizing the liquid. This energy (heat) balance is given by equation (3).

The change in fluid properties with temperature depression can be accounted for by rewriting equation (3) in incremental form as

$$w_n L_n = \left(1 - w_n - \sum_{i=2}^{n} w_{i-1}\right)\Delta H_{f,n} + \left(\sum_{i=2}^{n} w_{i-1}\right)\Delta H_{g,n}$$

or

$$w_n = \frac{\Delta H_{f,n}\left(1 - \sum_{i=2}^{n} w_{i-1}\right) + \Delta H_{g,n}\left(\sum_{i=2}^{n} w_{i-1}\right)}{\Delta H_{f,n} + L_n} \tag{4}$$

(The extra terms, usually neglected, account for vapor formed in prior increments.) The volumes of vapor and liquid and their ratio are as follows:

$$\mathcal{V}_v = \frac{\sum_{i=1}^{n} w_i}{\left(\rho_v\right)_n}$$

and

$$\mathcal{V}_l = \frac{1 - \sum_{i=1}^{n} w_i}{\left(\rho_l\right)_n}$$

or

$$\frac{\mathcal{V}_v}{\mathcal{V}_l} = \frac{\sum_{i=1}^{n} w_i}{\left(1 - \sum_{i=1}^{n} w_i\right)\left(\frac{\rho_v}{\rho_l}\right)_n} \tag{5}$$

With n equal to 1, the $\mathcal{V}_v/\mathcal{V}_l$ of equation (5) equals the B-factor of reference 4.

Thermodynamic tables of enthalpy change from a given initial liquid temperature, $\Delta H_{f,n}$ or $\Delta H_{g,n}$ in equation (4), also specify a corresponding change in saturation vapor pressure $\Delta h_{v,n}$. With such tables for Freon 114, nitrogen, and water (refs. 15, 18, and 21) and equations (4) and (5), figure 12 was determined. For convenience, small increments of Δh_v (~2 ft) were assumed and summed in a stepwise manner to yield the $\mathcal{V}_v/\mathcal{V}_l$ shown. The curves of figure 12 for several liquids at various initial temperatures

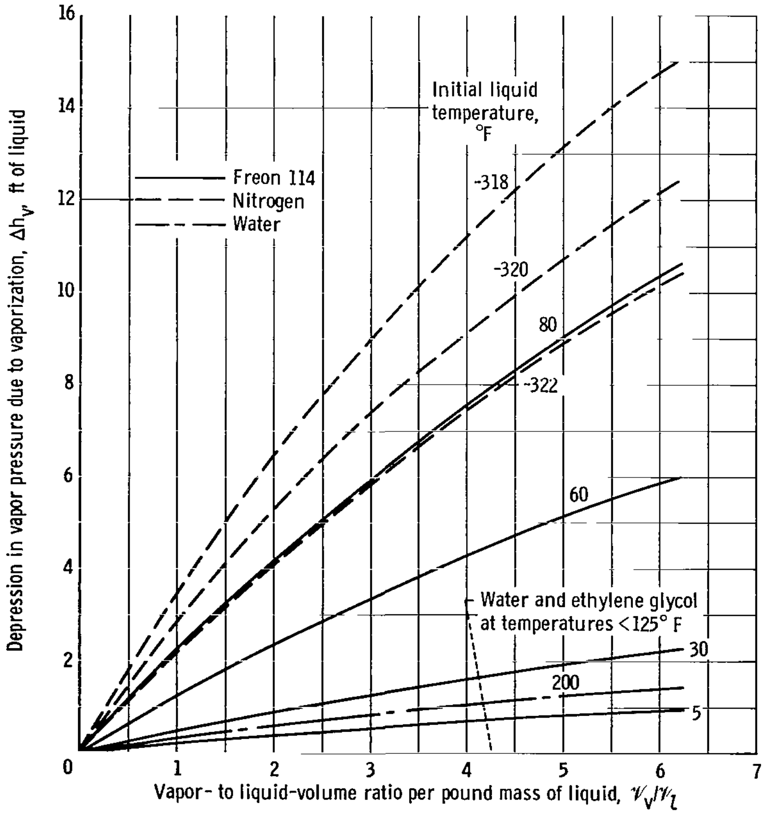


Figure 12. - Vapor pressure depression as function of amount of liquid vaporized for several liquids and temperatures based on equation (5).

are nonlinear because of the change in fluid properties as the equilibrium temperature drops as a result of vaporization.

A useful approximation of equation (5), and, thus, figure 12, is

$$\frac{\mathscr{V}_v}{\mathscr{V}_l} \cong \frac{1}{J}\left[\frac{\Delta h_v}{\left(\frac{\rho_v}{\rho_l}\right)^2\left(\frac{L^2}{c_l T}\right)}\right] \tag{6a}$$

or

$$\Delta h_v \cong J\left[\left(\frac{\rho_v}{\rho_l}\right)^2\left(\frac{L^2}{c_l T}\right)\left(\frac{\mathscr{V}_v}{\mathscr{V}_l}\right)\right] \tag{6b}$$

Equation (6) neglects ΔH_g and any change in liquid mass. Enthalpy change is expressed as $c_l \Delta T$, and Clapeyron's equation (which is derived for a reversible, isothermal, isobaric change of phase in ref. 22) was used to approximate the slope of the vapor-pressure temperature curve.

The vapor- to liquid-volume ratio $\mathscr{V}_v/\mathscr{V}_l$ for the experimental case is not measured or known directly, and thus the absolute values of figure 12 are for reference purposes only. However, useful predictions may result by implying an effective or reference value of $\mathscr{V}_v/\mathscr{V}_l$ from measured cavity-pressure depressions for one liquid, temperature, and velocity, and then estimating relative values of $\mathscr{V}_v/\mathscr{V}_l$ for other conditions and liquids. With these latter values of $\mathscr{V}_v/\mathscr{V}_l$, determinations of cavity pressure depressions relative to the reference data are possible.

Vapor volume $\mathscr{V}_v$ is assumed to be proportional to the product of cavity length Δx and cavity thickness δ_v. Liquid volume $\mathscr{V}_l$ is assumed proportional to the product of cavity length Δx and thickness of the liquid element δ_l supplying the heat of vaporization. Relative values of δ_l are estimated on the basis of the simplified theoretical heat-balance analysis developed in reference 12, wherein δ_l is shown to be proportional to the square root of the product of thermal diffusivity α and vaporization time. In the analysis of reference 12 it is assumed that the heat of vaporization is uniformly supplied by an element of liquid moving along the cavity surface with local flow velocity (proportional to free-stream velocity V_0). With vaporization time proportional to $\Delta x/V_0$, δ_l is proportional to $(\alpha\ \Delta x/V_0)^{0.5}$. The vapor- to liquid-volume ratio is, therefore, theo-

retically proportional to $\delta_v(V_0/\alpha \, \Delta x)^{0.5}$. Therefore, a volume ratio can be predicted relative to a reference value obtained from tests as follows:

$$\left(\frac{\mathscr{V}_v}{\mathscr{V}_l}\right)_{predicted} = \left(\frac{\mathscr{V}_v}{\mathscr{V}_l}\right)_{ref} \left(\frac{\alpha_{ref}}{\alpha}\right)^{0.5} \left(\frac{\Delta x_{ref}}{\Delta x}\right)^{0.5} \left(\frac{V_0}{V_{0,ref}}\right)^{0.5} \left(\frac{\delta_v}{\delta_{v,ref}}\right) \tag{7}$$

The last term in equation (7) is cavity thickness δ_v, which was not controllable or measured in this study. Because of the lack of data, δ_v is presently assumed invariant, and thus $(\delta_v/\delta_{v,ref})$ becomes 1 and hereinafter does not appear explicitly.

Experimental Freon 114 data are used to reevaluate the theoretically derived exponents in equation (7). Measurements of cavity pressure depression for Freon 114 are available for conditions in which only α (i.e., temperature) was varied, while V_0 and Δx were held constant. From these data (fig. 5) and the theoretical relation between Δh_v and $\mathscr{V}_v/\mathscr{V}_l$ (fig. 12), the exponent of α_{ref}/α in equation (7) can be determined. In a similar manner, the exponents for $V_0/V_{0,ref}$ and $\Delta x_{ref}/\Delta x$ can be evaluated by the analysis of data in which V_0 and Δx are the sole variables, respectively. From this procedure, the semiempirical expression (eq. (8)) was developed. For the present, it is offered as the best approach toward generalizing results for different temperatures and liquids in the venturi studied:

$$\left(\frac{\mathscr{V}_v}{\mathscr{V}_l}\right)_{predicted} = \left(\frac{\mathscr{V}_v}{\mathscr{V}_l}\right)_{ref} \left(\frac{\alpha_{ref}}{\alpha}\right)^{0.5} \left(\frac{\Delta x}{\Delta x_{ref}}\right)^{0.16} \left(\frac{V_0}{V_{0,ref}}\right)^{0.85} \tag{8}$$

The exponent for α_{ref}/α remains unchanged from that in equation (7), thus, the data and the simple unmodified theory agree regarding temperature effects. The cause of the change in exponents on the cavity-length ratio and on the velocity ratio is not clear at present. The use of various other liquids in the same venturi may indicate exponents slightly different from those of equation (8), based solely on Freon 114; the use of other model shapes (flow fields) may also change the exponents. However, the general method used herein to predict volume ratios and cavity pressure depressions is expected to remain a part of any more comprehensive correlation.

Equation (8) is plotted for convenience in figure 13, with $(\alpha_{ref}/\alpha)^{0.5}$ as a parameter. Use of figures 12 and 13 will be demonstrated in the following paragraphs.

Experimental temperature trends compared with theory. - If temperature is the only variable, equation (7) is applicable because $\Delta x/\Delta x_{ref}$ and $V_0/V_{0,ref}$ are unity, and thus the empirical modifications of equation (8) are not involved. For a $2\frac{3}{4}$-inch cavity,

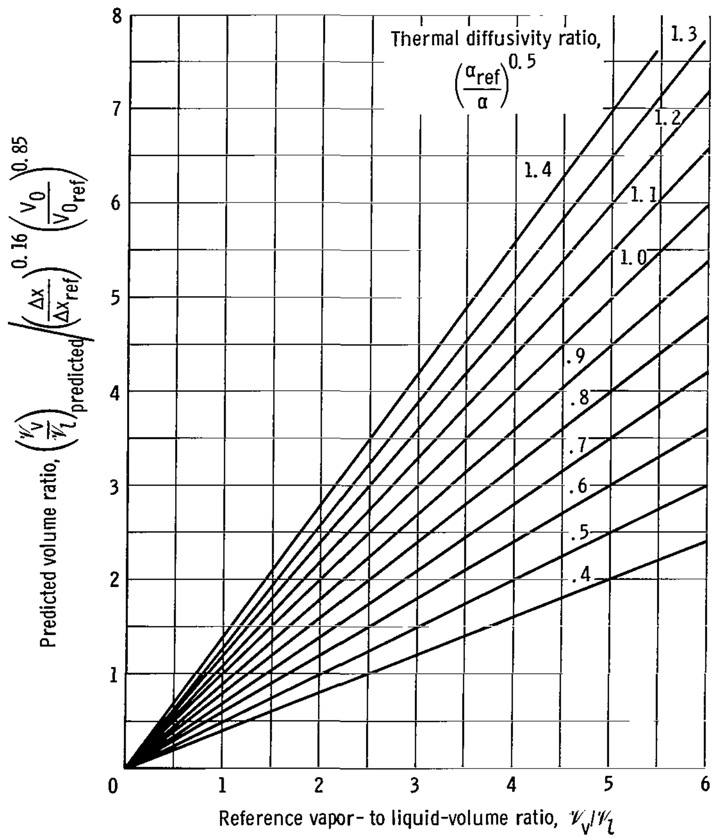


Figure 13. - Prediction of vapor- to liquid-volume ratio for other temperatures, liquids, velocities, and cavity lengths relative to reference volume ratio obtained from tests and figure 12.

the maximum pressure depression was about 8.5 feet of liquid for 78.8° F Freon 114 at a value of V_0 of 31.7 feet per second (fig. 5, p. 11). With Δh_v equal to 8.5 feet, figure 12 indicates a $\mathcal{V}_v/\mathcal{V}_l$ near 4.7. Values of the thermal diffusivity ratio $(\alpha_{ref}/\alpha)^{0.5}$ for 60°, 30°, and 5° F, relative to the test value for 78.8° F, are 0.97, 0.92, and 0.89, respectively. Therefore, from figure 13, and for the same cavity length and free-stream velocity, the predicted volume ratios for Freon 114 at several temperatures are 4.6 (at 60° F), 4.35 (at 30° F), and 4.15 (at 5° F). From figure 12 and the values of $\mathcal{V}_v/\mathcal{V}_l$, the maximum pressure depressions in the cavity are predicted to be 4.8 feet (60° F), 1.7 feet (30° F), and 0.7 foot (5° F). These predicted values are in good agreement with the experimental values of figure 5, where the comparable values are 5.1 feet (59.1° F), 1.8 feet (27.5° F), and 0.9 foot (5.7° F).

Table II summarizes these comparisons of experiment and theory regarding temperature level for Freon 114 as well as those regarding changes in velocity, liquid, and cavity length. The top row of table II lists the arbitrarily selected test values used as reference values from which all other tabulated values of Δh_v are predicted.

TABLE II. - COMPARISON OF EXPERIMENTAL AND THEORETICAL DATA

Liquid	Liquid temperature T, $^{\circ}F$	Thermal diffusivity, α, sq ft/hr	Free-stream velocity, V_0, ft/sec	Length of cavitated region, Δx, in.	Vapor pressure depression, Δh_v, ft		Vapor-to liquid-volume ratio, $\mathscr{V}_v/\mathscr{V}_l$ (b)
					Experimental (a)	Predicted (b)	
Freon 114	78.8	0.00152	31.7	$2\frac{3}{4}$	8.5	----	4.7
	59.1	.00162	31.7	↓	5.1	4.8	4.6
	27.5	.00179	31.7	↓	1.8	1.7	4.35
	5.7	.00192	31.7	↓	.9	.7	4.15
	78.1	.00152	19.0	↓	5.6	5.8	3.05
	78.4	.00152	44.2	↓	10.2	10.5	6.2
Nitrogen	-320.0	0.00320	20.1	2	4.8	5.3	2.0
	-319.6	.00320	25.1	4	6.3	7.0	2.8

[a]Figs. 5 to 7, or 10 according to fluid and conditions (experiment).
[b]Figs. 12 and/or 13 (theory).

The agreement between the varied temperature data and the simple unmodified theory indicates that the main factor which increases cavity pressure depression for higher temperature liquid Freon 114 is the increase in vapor density, as seen from equation (6b). Vapor density ρ_v increases by a factor near 4.5, while other fluid properties are little changed over the 5° to 80° F temperature range of Freon 114 studied.

Experimental velocity trends compared with theory. - As shown in figures 6 and 8, a nearly twofold increase in local cavity pressure depressions accompanies an increase in free-stream velocity from about 18.9 to 43.8 feet per second. The simple theories predict similar trends but indicate a velocity effect that is proportional to the 0.5 power (eq. (7)), whereas the experimental data show a velocity effect that is proportional to the 0.85 power (eq. (8)). By using the same reference values (table II, top row) and figures 12 and 13, the maximum cavity pressure depression for 78.1° F Freon 114 at 19.0 feet per second is predicted to be 5.8 feet of liquid; at 44.2 feet per second, the predicted value is 10.5 feet of liquid. The comparable values from tests are 5.6 feet (at 19.0 ft/sec, fig. 6(a)) and 10.2 feet (at 44.2 ft/sec, fig. 6(b)). The increased Δh_v with increased V_0 is believed to be a result of the heat of vaporization being drawn from a relatively thinner liquid layer because of the shorter times available at the higher velocities. Thus, the temperature depressions of the thinner layer are larger, which result in correspondingly larger pressure depressions.

Experimental trends of different liquids compared with theory. - As previously discussed, the water and the glycol data were limited to liquid temperatures $\leq 125^{\circ}$ F, and

in this range measured cavity pressure and temperature depressions are negligible. The same result is predictable from the analysis herein (fig. 12, p. 21).

Figure 12 indicates that, for the same volume ratio $\mathcal{V}_v/\mathcal{V}_l$, the highest temperature Freon 114 data available, approximately 80° F, should approximate the lowest temperature nitrogen data available, -320° F. On this basis, a comparison at constant V_0 near 19 feet per second of the 78.1° F data of figure 6(a) (p. 12) with the -320° F data of figure 10 (p. 16) appears reasonable because the Freon 114 data for a $2\frac{3}{4}$-inch cavity length falls between the 2- and 4-inch-long nitrogen cavitation. (Photographs for comparison were previously shown in fig. 11, p. 17.) Starting with the Freon 114 reference values (table II, top row) the Δh_v is 8.5 feet, from figure 5 (p. 11), and the reference $\mathcal{V}_v/\mathcal{V}$ is 4.7, from figure 12. As given in table II for -320° F nitrogen, α is 0.0032 square foot per hour and for 78.8° F Freon 114, α is 0.00152 square foot per hour. Thus, the parameter $(\alpha_{ref}/\alpha)^{0.5}$ has the value of 0.68. Therefore, from figure 13 (p. 24), $\mathcal{V}_v/\mathcal{V}_l$ becomes 3.2 for a nitrogen Δx of $2\frac{3}{4}$ inches at V_0 of 31.7 feet per second. Thus far, $\mathcal{V}_v/\mathcal{V}_l$ has been modified for change of liquid only. Next, with Δx changed from $2\frac{3}{4}$ to 2 inches and V_0 changed from 31.7 to 20.1 feet per second, figure 13 (or eq. (8)) predicts a $\mathcal{V}_v/\mathcal{V}_l$ of about 2.0, which, with figure 12, yields a maximum pressure depression of 5.3 feet of liquid. The nitrogen data of figure 10 indicate a value near 4.8 feet. Other reference values yield essentially the same kind of results.

The quantitative effect of α on $\mathcal{V}_v/\mathcal{V}_l$ is shown in table II. For example, the value of α for -320° F nitrogen is about twice the value of α for 78.1° F Freon 114 which, for other parameters being equal, results in a $\mathcal{V}_v/\mathcal{V}_l$ for nitrogen of about two-thirds that for Freon 114.

Similar comparisons between Freon 114 and nitrogen at other temperatures and velocities (table II) confirm measured trends and, generally, yield good quantitative agreement for cavity pressure depressions. Thus, it is concluded that the simple theoretical analyses, with some empirical modifications (which are based only on Freon 114 data), are useful in predicting cavity pressure depressions for other temperatures and liquids if cavity depression data are measurable and available for at least one liquid flowing through the same model. Improved quantitative predictions will probably require a more detailed analysis like that suggested in the discussion of reference 23.

Estimation of free-stream static pressure for similar cavity lengths in other liquids. - As previously presented in table I, $K_{c,min}$ for similar cavitation with several liquids can be reasonably approximated for the venturi by a single value, 2.37 (cavities > 1 in. long). With $K_{c,min}$ of 2.37 and with figures 12 and 13 to predict trends in cavity pressure depressions, h_0 can be estimated. To illustrate the method, h_0 will be estimated for -320° F nitrogen, a 4-inch cavity, and a V_0 of 19.2 feet per second. Equation (2) can be rearranged so that

$$h_0 = \frac{V_0^2}{2g}\left(K_{c,min}\right) - \left(h_v - h_{c,min}\right) + h_v \qquad (2a)$$

At a V_0 of 19.0 feet per second, Freon 114 at 78.1° F yields, for a $2\frac{3}{4}$-inch cavity, a value of $h_v - h_{c,min}$ from figure 6(a) of 5.6 feet of liquid; this value and the data in figure 12 (p. 21) establish a reference volume ratio $\mathscr{V}_v/\mathscr{V}_l$ of 2.9. From figure 13 (p. 24), for a value of the parameter $(\alpha_{ref}/\alpha)^{0.5}$ of 0.68, a V_0 of 19.2 feet per second, and a 4-inch cavity $((\Delta x/\Delta x_{ref})^{0.16}$ of 1.06), the $\mathscr{V}_v/\mathscr{V}_l$ predicted for -320° F nitrogen is about 2.1, which, with figure 12, predicts $h_v - h_{c,min}$ of 5.5 feet of liquid. The value of h_v is 44.2 feet of liquid, therefore h_0 from equation (2a) is estimated to be 52.3 feet of liquid. From figure 10 (p. 16), the experimental h_0 value was 52.1 feet of liquid nitrogen. For the same h_0 of 52.1 feet of liquid, it is estimated that water at a temperature of about 227° F would also yield a 4-inch cavity at V_0 of 19.2 feet per second.

Geometric similarity of the cavitated region is an implied prerequisite throughout these extrapolations to other liquids and conditions. For example, estimates of h_0 for nitrogen at $V_0 > 30$ feet per second are not accurate because $K_{c,min}$ is no longer near a value of 2.37 because of the dissimilar cavity-leading-edge location. At present, however, it is not generally known what conditions or fluid properties will result in dissimilar geometry of cavitation, particularly in the critical leading-edge region. Further study is required to define the limits of application of equation (2a).

Evaluation of assumptions in theoretical analyses. - Steady and adiabatic flow and negligible body forces are believed to be reasonably satisfied. The flow was steady in the time-averaged sense of the measurements made. No liquid tension was assumed in the theory, and this is probably not true experimentally. As reported elsewhere (refs. 1 to 3 and 14), liquid tension exists immediately prior to incipient cavitation, although its effect on pressure depressions in subsequent well-developed cavitation is not known at present, nor are the effects of possible liquid tensions upstream concurrent with developed cavities.

Also, the fluid was assumed to be in thermodynamic equilibrium for the cavitation process. For all the fluids and ranges of conditions studied, this equilibrium was reasonably well satisfied, as evidenced by agreement of temperature and pressure measurements within the cavitated region. Because vaporization and condensation occur at finite rates, it is expected that conditions of thermodynamic equilibrium are less likely to be realized as local velocity increases. For the venturi and liquids studied, V_0 to about 45 feet per second (throat or local velocities near 90 ft/sec) did not cause any noticeable trends toward nonequilibrium.

The assumption of uniform cooling along the cavity length (ref. 12) seems to be contradicted by the increasing pressure from the leading to the trailing edge within the cavity.

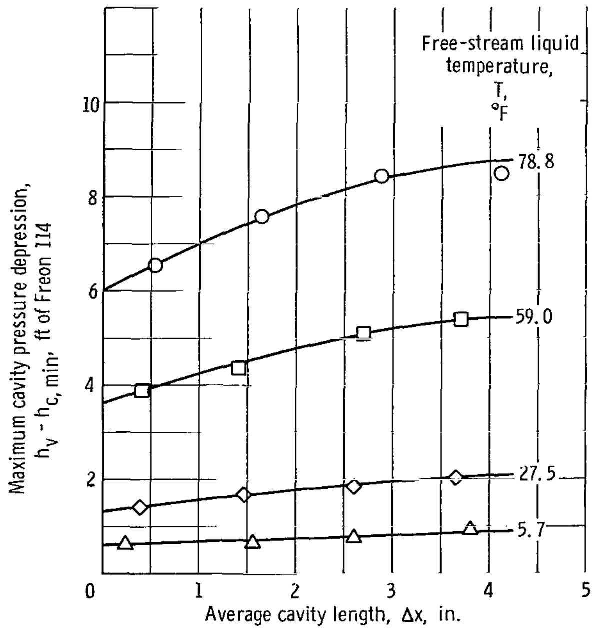


Figure 14. - Typical effect of cavity length on maximum cavity pressure depression for Freon 114. Free-stream velocity, 33.3 feet per second at zero-inch to 30.0 feet per second at 4 inches.

Also, it appears that cavity thickness δ_v may not be invariant, as assumed in this report, but some function of cavity length Δx and/or free-stream velocity V_0. This could account, in part at least, for the exponent on $\Delta x/\Delta x_{ref}$ and $V_0/V_{0,ref}$ in equation (8) being different from those theoretically predicted by equation (7). These discrepancies between assumptions and experimental results do not appear to detract from the usefulness of the method for the present application.

CONCLUDING REMARKS

The modeling or similarity parameter generally used for the inception (first visible appearance) of cavitation is

$$K_{iv} = \frac{h_0 - h_v}{\frac{V_0^2}{2g}}$$

where h_v denotes vapor pressure corresponding to the free-stream or bulk-liquid temperature, and h_0 and V_0 are the free-stream values that produced the incipient cavitation (refs. 17 and 23). With this definition, the incipient cavitation results for Freon 114 varied as much as 30 percent with an increase in bulk-liquid temperature from 0^o to 80^o F (ref. 2). For the same liquid, model, velocity, and temperature range, sizeable changes in developed-cavity pressure (approximately local vapor pressure) were measured because of the varying thermal effects of vaporization. Because incipient cavitation occurs near the minimum noncavitating pressure location (see ref. 2) and represents a cavity length that approaches zero, it seems reasonable to extrapolate the measured $h_{c,min}$ values to zero cavity length and use them in place of h_v for a new incipient cavitation parameter. Thus, for incipient cavitation, K_{iv} is replaced by $K_{ic,min}$ in a manner parallel to that for developed cavitation where K_v was replaced by $K_{c,min}$, as previously discussed. Thus, figure 14 presents typical $h_{c,min}$ data as a function of cavity length and free-stream temperature from which the zero length value is obtained for figure 15. Figure 15 summarizes the effects of V_0 and T on $h_{c,min}$ at zero cavity

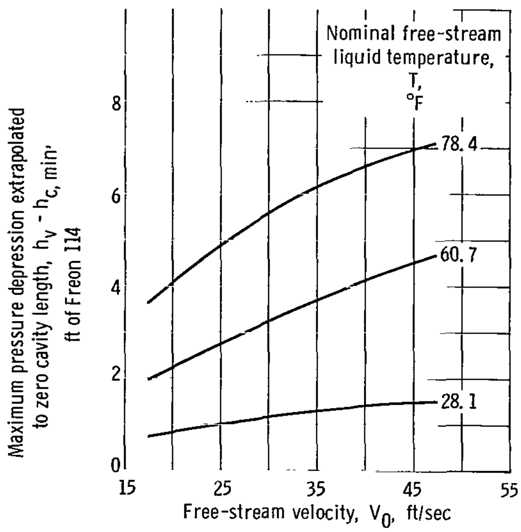
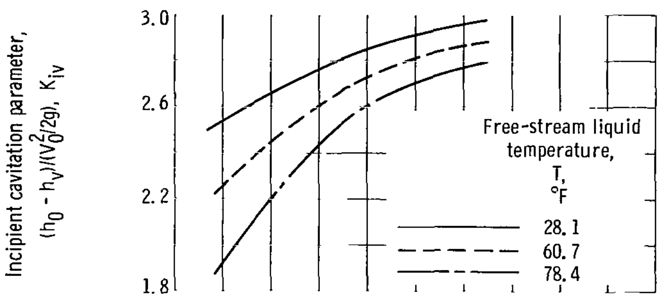
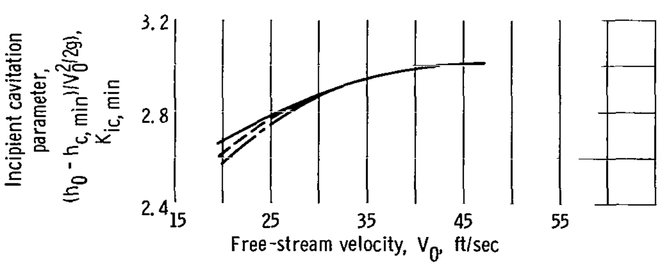


Figure 15. - Effect of free-stream velocity and liquid temperature on maximum pressure depression extrapolated to incipient cavity size for Freon 114.



(a) Incipient cavitation parameter based on vapor pressure h_v, (ref. 2).



(b) Incipient cavitation parameter based on minimum cavity pressure, $h_{c,min}$, (fig. 15).

Figure 16. - Effect of reference pressure on incipient cavitation parameter for Freon 114.

length for all the Freon 114 data. Finally, figure 16 compares $K_{ic,min}$ with K_{iv}, and the 30-percent spread in K_{iv} due to temperature has been eliminated. Although $h_{c,min}$ is not generally available or predictable for an arbitrary fluid and model, the improved correlation (using $h_{c,min}$) noted in figure 16 suggests the possible importance of accounting for thermal effects of vaporization of certain liquids even for the incipient cavitation level. The growth-retarding trends of evaporative cooling within a bubble are also evident in the classical equations describing bubble growth, if heat-transfer terms are included, as shown in reference 24.

For Freon 114, $K_{ic,min}$ in figure 16 described essentially one curve for a range of temperatures, but varies with velocity (in a different manner than $h_v - h_{c,min}$ for developed cavity flow previously discussed). A different $K_{ic,min}$ curve would apply for nitrogen (see ref. 1), and another, for water (see ref. 3). Thus, a more general method of predicting incipient cavitation for different liquids is lacking at present, in part, because such factors as nuclei content, surface tension effects, viscosity, etc., are neglected herein. However, for a liquid tested at one temperature and over a range of velocities, reasonably accurate estimates of h_0 for a given velocity might be made for other temperatures by using figures 12 and 13 (pp. 21 and 24) in a manner similar to that previously described for estimating h_0 for developed cavitation of

other liquids. (For application to incipient cavitation, Δx in fig. 13 can approach but cannot equal zero.)

SUMMARY OF RESULTS

Temperature and pressure measurements within regions of well-developed cavitation of Freon 114 (dichlorotetrafluoroethane) flowing through a venturi were made and compared with other liquids and with theoretical analyses to yield the following principal results:

1. Temperatures and pressures within cavitated regions were in thermodynamic equilibrium at values less than free-stream (approach section) values of liquid temperature and corresponding vapor pressure. For Freon 114, the maximum and average cavity pressure depressions increased almost directly with increased free-stream velocity at constant free-stream liquid temperature. At constant velocity, the maximum pressure depression below free-stream vapor pressure increased greatly as the Freon 114 temperature was increased. The maximum measured cavity pressure depression was 10.2 feet of liquid for 78.4° F Freon 114.

2. For the same free-stream velocity and cavity length, the maximum cavity pressure depression (in ft of liquid) for 78° F Freon 114 was about the same as that for -320° F nitrogen, while for water and for ethylene glycol at temperatures $\leq$ 125° F, measured cavity depressions were negligible. Such comparison can be predicted reasonably well by a simplified theoretical analysis that considers the fluid-property effects on the vapor and liquid volumes involved in the cavitation.

3. Similarity parameters for cavitation were developed and evaluated herein by accounting for thermal effects of vaporization. For geometrically similar developed cavitation in Freon 114, nitrogen, and water, a nearly single value was obtained for a cavitation parameter that used the minimum measured cavity pressure as a reference. The incipient cavitation parameter is likewise improved by using the minimum cavity pressure as a reference.

4. A method for estimating the minimum cavity pressure for developed cavitation in the venturi with an untested liquid is presented. The method depends on knowing a value of minimum cavity pressure for one test liquid. Similarly, a method for estimating mininum cavity pressure for incipient cavitation with one liquid at untested temperature is possible, providing that known values of minimum cavity pressure for this liquid are available at some temperature. Both methods require that the test liquids exhibit measurable cavity pressure depressions below free-stream vapor pressure.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 7, 1966.

APPENDIX - SYMBOLS

c_l specific heat of liquid, Btu/(lb mass)($^{\circ}$R)

C_p noncavitating pressure coefficient, $(h_x - h_0)/(V_0^2/2g)$

g acceleration due to gravity, 32.2 ft/sec^2

ΔH_f change in specific enthalpy of liquid, Btu/lb mass

ΔH_g change in specific enthalpy of vapor, Btu/lb mass

h_c pressure in cavitated region, ft of liquid abs

h_v vapor pressure corresponding to free-stream liquid temperature, ft of liquid abs

Δh_v decrease in vapor pressure because of vaporization, ft of liquid

h_x static pressure at x, ft of liquid abs

h_0 free-stream static pressure at X of 3.448 (approach section, fig. 1) ft of liquid abs

J mechanical equivalent of heat, 778 (ft)-(lb force)/Btu

K cavitation parameter defined by equation (1)

$K_{c,min}$ developed cavitation parameter based on minimum cavity pressure, $(h_0 - h_{c,min})/(V_0^2/2g)$

$K_{ic,min}$ incipient cavitation parameter based on minimum cavity pressure, $(h_0 - h_{c,min})/(V_0^2/2g)$

K_{iv} incipient cavitation parameter based on free-stream vapor pressure, $(h_0 - h_v)/(V_0^2/2g)$

K_v developed cavitation parameter based on free-stream vapor pressure, $(h_0 - h_v)/(V_0^2/2g)$

k thermal conductivity of saturated liquid, (Btu)(ft)/(hr)(sq ft)($^{\circ}$F)

L latent heat of vaporization, Btu/lb mass

T free-stream liquid temperature, $^{\circ}$F

V_0 free-stream velocity at X of 3.448 (approach section, fig. 1), ft/sec

$\mathcal{V}_l$ volume of saturated liquid defined by equation (5), cu ft

$\mathcal{V}_v$ volume of saturated vapor defined by equation (5), cu ft

w vaporized fraction of 1-pound mass of liquid involved in cavitation process (defined by eq. (4)), lb mass

X axial distance from test section inlet (see fig. 1), in.

x axial distance from minimum noncavitating pressure location ($X = 4.307$ in.), in.

Δx	length of cavitated region, in.
α	thermal diffusivity, $k/\rho_l c_l$, sq ft/hr
δ_l	thickness of liquid element, in.
δ_v	thickness of vapor cavity, in.
ρ_l	saturated liquid density, lb mass/cu ft
ρ_v	saturated vapor density, lb mass/cu ft

Subscripts:

i	1, 2, 3, etc.
l	liquid
min	minimum
n	last increment in a sum
ref	reference value obtained from experimental tests
sat	saturation at h_0

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